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(71) Applicant: APPLIED MATERIALS, INC.
Santa Clara California 95054-3299 (US)

(72) Inventors:
- Qian, Xue-Yu
  Milpitas, California 95035 (US)
- Sato, Arthur H.
  Santa-Clara, California 95054 (US)

(74) Representative: Bayliss, Geoffrey Cyril et al
BOULT, WADE & TENNANT
27 Furnival Street
London EC4A 1PQ (GB)

(54) Plasma reactors for processing semi-conductor wafers

(57) The disclosure relates to a coil antenna (30) for radiating RF power supplied by an RF source (64) into a vacuum chamber (54) of an inductively coupled plasma reactor which processes a semiconductor wafer in the vacuum chamber. The reactor has a gas supply inlet (56) for supplying processing gases into the vacuum chamber. The coil antenna includes plural concentric spiral conductive windings (32, 34, 36), each of the windings having an interior end (32a, 34a, 36a) near an apex of a spiral of the winding and an outer end (32b, 34b, 36b) at a periphery of the spiral of the winding, and a common terminal (38) connected to the interior ends of the plural concentric spiral windings. The RF power source is connected across the terminal and the outer end of each one of the windings.

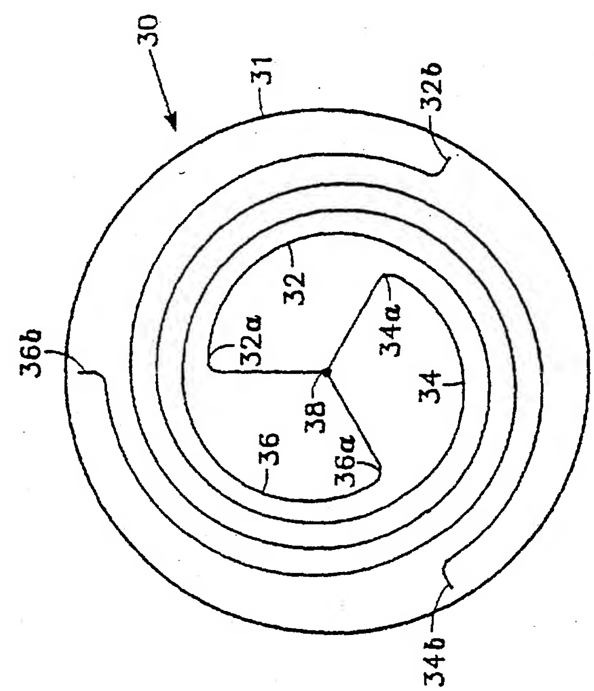

FIG. 3A

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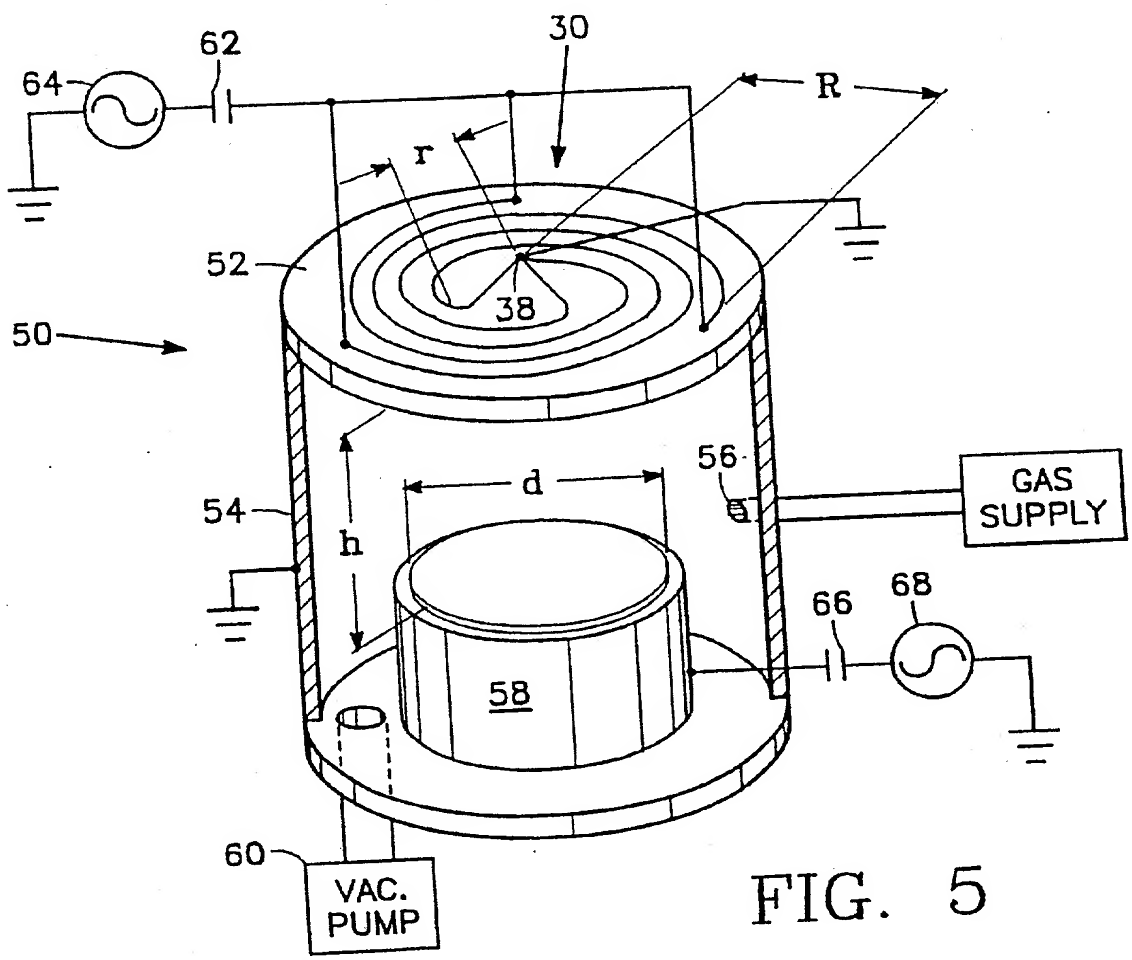


FIG. 5

Description

The invention is related to fabrication of microelectronic integrated circuits with a inductively coupled RF plasma reactor and particularly to such reactors having coiled RF antennas providing a highly uniform plasma distribution.

Inductively coupled plasma reactors are employed where high density inductively coupled plasmas are desired for processing semiconductor wafers. Such processing may be etching, chemical vapor deposition and so forth. Inductively coupled reactors typically employ a coiled antenna wound around or near a portion of the reactor chamber and connected to an RF power source. In order to provide a uniform etch rate or deposition rate across the entire surface of a wafer, the plasma density provided by the coiled antenna must be *uniform across the surface of the semiconductor wafer. One attempt to provide such a uniform field is to wind the coiled antenna in a flat disk parallel to overlying the wafer, as disclosed in U.S. Patent No. 4,948,458 to Ogle. This concept is depicted in FIG. 1.

One problem with the flat coiled antenna of FIG. 1 is that there is a large potential difference between the center of the antenna and the circumferential edge thereof, with the result that the plasma can have a high ion density or "hot spot" over the center of the wafer and a lower ion density at the wafer periphery. This in turn causes the etch rate --or deposition rate-- to be nonuniform across the wafer surface. One way of ameliorating this problem is to limit the power applied to the antenna coil to a few hundred watts so as to minimize the plasma non-uniformity. This approach is not completely satisfactory because it limits the etch rate (or deposition rate), thereby reducing throughput or productivity of the reactor, and moreover does not solve the problem of process non-uniformity across the wafer surface.

Another problem with inductively coupled reactors is that any high voltage applied to the antenna coil leads to capacitive coupling of RF power to the plasma. In other words, capacitive coupling of RF power from the coiled antenna to the plasma increases with the voltage on the coiled antenna. Such capacitive coupling can increase the ion kinetic energy which makes it difficult for the user to precisely control ion kinetic energy and thereby control sputtering rate or etch rate. Capacitive coupling is particularly pronounced in the flat disk coil antenna of FIG. 1.

Therefore, there is a need for an inductively coupled plasma reactor having a coiled antenna which provides a highly uniform plasma across the wafer surface at high power with only minimal capacitive coupling.

A coil antenna is provided for radiating RF power supplied by an RF source into a vacuum chamber of an inductively coupled plasma reactor which processes a semiconductor wafer in the vacuum chamber, the reactor having a gas supply inlet for supplying processing gases into the vacuum chamber, the coil antenna including plural concentric spiral conductive windings, each of the windings having an interior end near an apex of a spiral of the winding and an outer end at a periphery of the spiral of the winding, and a common terminal connected to the interior ends of the plural concentric spiral windings, the RF power source being connected across the terminal and the outer end of each one of the windings. In a preferred embodiment, the RF power source includes two terminals, one of the two terminals being an RF power terminal and the other of the two terminals being an RF return terminal which is connected to ground, the common terminal of the plural concentric spiral conductive windings being connected to one of the RF source terminals and the outer ends of the plural concentric spiral conductive windings being connected to the other RF source terminal.

In a first embodiment, the reactor chamber includes a planar ceiling and the antenna coil has a planar disk shape and lies on an exterior surface of the ceiling. In a second embodiment, the reactor chamber includes a cylindrical side wall and the antenna coil has a cylindrical shape and is helically wound around a portion of the cylindrical wall. In a third embodiment, the reactor includes a dome-shaped ceiling and the antenna coil has a dome shape and is helically wound around, lies on and is congruent with at least a portion of the dome-shaped ceiling. In a fourth embodiment, the reactor includes a truncated dome-shaped ceiling and the antenna coil has a truncated dome shape and is helically wound around, lies on and is congruent with at least a portion of the truncated dome-shaped ceiling. In a fifth embodiment, the reactor chamber includes a planar ceiling and a cylindrical side wall and one portion of the antenna coil is planar and overlies the planar ceiling while another portion of the antenna coil is cylindrical and is helically wound around at least a portion of the cylindrical side wall. In a sixth embodiment, the reactor includes a dome-shaped ceiling and a cylindrical side wall and one portion of the antenna coil is dome-shaped and overlies and is congruent with the dome-shaped ceiling and another portion of the coil antenna is cylindrical and is wound around at least a portion of the cylindrical side wall. In a seventh embodiment, the reactor includes a truncated dome-shaped ceiling and a cylindrical side wall and one portion of the antenna coil is truncated dome-shaped and overlies and is congruent with the truncated dome-shaped ceiling and another portion of the coil antenna is cylindrical and is wound around at least a portion of the cylindrical side wall.

Preferably, the plural windings are of about the same length. In one embodiment, the coil antenna includes three of the windings. Preferably, the inner ends are circumferentially spaced from one another at equal intervals and wherein the outer ends are circumferentially spaced from one another at equal intervals. A bias RF source may be connected to the wafer pedestal.

The following is a description of some specific embodiments of the invention reference being made to the accompanying drawings in which:

FIG. 1 is a simplified diagram of a coiled antenna for an inductively coupled plasma reactor of the prior art.

FIG. 2 is a simplified diagram of a coil antenna having its windings connected in parallel across an RF source.

FIG. 3A is a top view of a flat disk coil antenna for a plasma reactor in accordance with a first embodiment of the invention.

FIG. 3B is a top view of a flat disk coil antenna corresponding to FIG. 3A but having a greater number of windings.

FIG. 4 is a side view corresponding to FIG. 3A.

FIG. 5 is a perspective cut-away view of an inductively coupled plasma reactor employing the coiled antenna of the embodiment of FIG. 3A.

FIG. 6 is a perspective view of a cylindrical coil antenna in accordance with a second embodiment of the invention.

FIG. 7 is a perspective view of a coil antenna in accordance with a third embodiment of the invention which is a variant of the cylindrical coil antenna of FIG. 6 in that the cylindrical coil is continued over the ceiling of the reactor.

FIG. 8 is a perspective view of a coil antenna in accordance with a fourth embodiment of the invention having a dome shape.

FIG. 9 is a perspective view of a coil antenna in accordance with a fifth embodiment which is a variant of the cylindrical coil antenna of FIG. 6 and the dome antenna of FIG. 8.

FIG. 10 is a perspective view of a coil antenna in accordance with a sixth embodiment having a truncated dome shape overlying a truncated dome-shaped ceiling of a plasma reactor.

FIG. 11 is a perspective view of a coil antenna in accordance with a seventh embodiment having a truncated dome-shaped portion overlying a truncated dome-shaped reactor ceiling and a cylindrical portion surrounding the reactor side wall.

FIG. 12 is a perspective view of an embodiment of the invention having a truncated dome ceiling forming a chamfered corner along the circumference of the ceiling.

FIG. 13 is a perspective view of a variation of the embodiment of FIG. 12 including a cylindrical winding.

FIG. 14 is a perspective view of an embodiment of the invention having a shallow or partial dome-shaped ceiling.

FIG. 15 is a perspective view of a variation of the embodiment of FIG. 14 including a cylindrical winding.

FIG. 16 is a perspective view of an embodiment of the invention having a shallow dome-shaped ceiling with a chamfered corner along its circumference.

FIG. 17 is a perspective view of a variation of the embodiment of FIG. 16 including a cylindrical winding.

FIG. 18 contains superimposed graphs of ion current measured at the wafer surface as a function of radial position from the wafer center for various types of reactors of the prior art and corresponding graphs for a reactor incorporating the present invention.

FIG. 19 contains superimposed graphs of ion current measured at the wafer surface as a function of reactor chamber pressure for different reactors of the prior art.

FIG. 20 contains superimposed graphs of ion current measured at the wafer surface as a function of reactor chamber pressure for different reactors of the prior art and corresponding graphs for a reactor incorporating the present invention.

FIG. 21 contains superimposed graphs of ion current measured at the wafer surface as a function of reactor chamber pressure for different reactors of the prior art.

In an inductively coupled plasma reactor having an RF antenna coil adjacent the reactor chamber, it is a goal of the invention to reduce the voltage on the coil. One possible approach to reduce coil voltage is to reduce the amount of inductance in the winding of the coil antenna. This would reduce the potential V across each winding (since $V = L\ di/dt$, where L is the winding inductance and i is the winding current), this reduction in electric potential reducing capacitive coupling to the plasma. FIG. 2 illustrates one way of accomplishing this by connecting all of the coil windings 10, 12, 14 in parallel across the RF power source 16, 18 via conductors 20, 22. One end 10a, 12a, 14a of each winding is connected to the conductor 20 while the other end 10b, 12b, 14b is connected to the other conductor 22. The problem is that the gap 24 between the conductors 20, 22 gives rise to a discontinuity in the RF field. Thus, for example, in a plasma etch reactor employing the coiled antenna of FIG. 2, the discontinuity of the coil can often cause azimuthal asymmetry in the plasma density across the wafer surface. Accordingly, the coil antenna of FIG. 2 does not provide a uniform plasma density and therefore does not fulfill the need.

Referring to FIGS. 3A and 4, a coil antenna 30 overlies the ceiling of a reactor chamber 31, the coil antenna 30 having plural concentric spiral windings 32, 34, 36 connected in parallel across a capacitor 62 and an RF source 64. The windings 32, 34, 36 have inner ends 32a, 34a, 36a near the center of the spirals and outer ends 32b, 34b, 36b at the peripheries of the spirals. The inner ends 32a, 34a, 36a are connected together at a common apex terminal 38. In the preferred embodiment, the common apex terminal 38 is connected to ground while the outer winding ends 32b, 34b, 36b are connected to the RF source 64. As shown in FIG. 4, the straight central inner arms of the windings 32, 34, 36 preferably wick vertically upwardly away from the reactor top to the apex terminal 38 by a vertical distance v of about 2 cm. FIG. 3B illustrates a 5-winding version of the coil antenna of FIG. 3A, including concentric windings 32, 33, 34, 35, 36 with inner endings 32a, 33a, 34, 35a, 36a and outer endings 32b, 33b, 34b, 35b, 36b.

FIG. 5 illustrates an inductively coupled plasma reactor including a cylindrical vacuum chamber 50 having a flat disk insulating ceiling 52, a grounded conductive cylindrical side wall 54, a gas supply inlet 56 and a wafer pedestal 58. A vacuum pump 60 pumps gas out of the vacuum chamber. The coil antenna 30 of FIG. 3A rests on the ceiling 52. An RF power source 64 applies power through the capacitor 62 to the outer winding ends 32, 34, 36 while the common terminal 38 is grounded. A bias RF power source 66, 68 is connected to the wafer pedestal 58 to control ion kinetic energy.

In a preferred implementation of the embodiment of FIG. 5, the circular windings become straight radial arms terminating in the apex terminal 38, the arms extending along a radius r (FIG. 5) of about 2.5 cm. The outermost one of the windings 32, 34, 36 has a radius R (FIG. 5) of about 35 cm in those cases in which the wafer diameter d (FIG. 5) is about 20 cm. The height h (FIG. 5) of the coil antenna above the wafer is preferably about 5.0 cm to 7.5 cm. Preferably, each one of the coil windings 32, 34, 36 makes 1.5 turns. The number of windings per length of radius, which in the embodiment of FIG. 5 is 1.5/26 cm^{-1}, may be changed so as to desirably adjust the plasma density distribution across the wafer surface.

FIG. 6 illustrates a cylindrical version 60 of the coil antenna 30 of FIG. 3A, which also has plural concentric spiral windings 32', 34', 36' each wrapped around an insulating portion of the cylindrical side wall 54 of the reactor of FIG. 5. The plural concentric windings 32', 34', 36' have respective inner ends 32a', 34', 36a' terminating in a common apex terminal 38a, as well as outer ends 32b', 34b', 36b' terminating equidistantly from each other at locations about the lower sidewall of the reactor chamber. FIG. 7 illustrates another version of the cylindrical antenna 60, in which inner ends 32a', 34a', 36a' of the antenna 60 continue in spiral fashion across the top of the reactor in a form much as in FIG. 5 to the common apex terminal 38b, thus forming a continuous single cylindrical coil antenna 70 extending not only over portions of the cylindrical wall 54 but also over the ceiling 52 of the reactor. Preferably, each winding 32', 34', 36' makes a smooth transition at the corner between the ceiling and the cylindrical sidewall, in the manner illustrated in the drawing.

FIG. 8 illustrates a dome-shaped version 80 of the coil antenna 30 of FIG. 3A for use with a version of the reactor of FIG. 5 in which the ceiling 52 is dome-shaped. FIG. 9 illustrates how the dome-shaped coil antenna 80 may be integrated with the cylindrical shaped coil antenna 60 to form a single antenna 90 covering both the dome-shaped ceiling and cylindrical side wall of the reactor of the embodiment of FIG. 8. The windings make a smooth transition from the dome-shaped ceiling to the cylindrical sidewall in the manner illustrated in the drawing. FIG. 10 illustrates a modification of the coil 80 of FIG. 8 in which the dome-shaped ceiling is truncated so as to have a flattened apex. FIG. 11 illustrates a modification of the coil of FIG. 9 in which the dome-shaped ceiling is truncated so as to have a flattened apex.

The windings 32, 34, 36 are spaced from one another by a sufficient spacing to prevent arcing therebetween. In order to provide an azimuthal symmetrical RF power feeding and minimum potential difference between adjacent winding along the entire lengths thereof, all windings 32, 34, 36 preferably are of the same length. In the illustrated embodiments, the spacings between windings are equal and are uniform throughout the antenna coil. However, the invention may be modified by varying the winding-to-winding spacings so as to be different at different locations or to differ as between different pairs of windings.

While the invention has been described with reference to preferred embodiments having three concentric spiral windings 32, 34, 36, other embodiments of the invention may be made with as few as two such windings, four such windings or any desired number of windings, provided the requisite winding-to-winding spacing is maintained to avoid arcing. A greater number of spiral windings provides a more uniform RF field and in some cases more uniform plasma ion density across the wafer surface.

FIG. 12 illustrates a variation of the embodiment of FIG. 10 in which the ceiling 52 has a central flat region 52a surrounded by an annular chamfer 52b which provides a smooth transition from the horizontal flat region 52a to the vertical side wall 54. This in turn helps the windings 32, 33, 34, 35, 36 make a smooth transition as well. An annular portion of the coil antenna overlies and conforms with the corner chamfer. Furthermore, the embodiment of FIG. 12 has five concentric windings 32, 33, 34, 35, 36 with outer ends 32b, 33b, 34b, 35b, 36. FIG. 13 illustrates a variation of the embodiment of FIG. 12 in which concentric windings 32', 33', 34', 35', 36' make a smooth transition at the corner chamfer from the flat portion of the ceiling 52 to the cylindrical side wall, each of these windings including a first portion overlying the flattened central part 52a of the ceiling 52, a second portion overlying the corner chamfer 52b of the ceiling 52 and a third portion wrapped around the cylindrical side wall 54. The winding outer ends 32b', 33b', 34b', 35b', 36b' defining the bottom of the coil antenna are disposed at about the same height as the top of the wafer pedestal 58 and are connected to the output terminal of the RF source through the capacitor 62. The pitch of the windings may vary with location so that, as one example, the windings on the top may be at one pitch while the winding along the cylindrical side wall may be at a different pitch, thus providing greater control over the plasma formation.

FIG. 14 illustrates a variation of the embodiment of FIG. 12 having flattened dome-shaped ceiling, whose arc subtends an angle substantially less than 180 degrees, for example about 90 degrees. In contrast, for example, the dome-shaped ceiling of FIG. 10 subtends approximately 180 degrees of arc. FIG. 15 illustrates a variation of the em-

bodiment of FIG. 13 also having flattened dome-shaped ceiling, whose arc subtends an angle substantially less than 180 degrees, for example about 90 degrees.

FIG. 16 illustrates an embodiment combining a flattened central dome 52a' like that of FIG. 14 with an outer corner chamfer 52b' like that of FIG. 12. FIG. 17 illustrates a variation of the embodiment of FIG. 16 in which the windings make a smooth transition at the corner chamfer 52b from the ceiling 52 to the cylindrical side wall 54. The embodiments of FIGS. 12-17 are illustrated as having 5 concentric windings each, in contrast with the 3 concentric windings of the embodiments of FIGS. 3-11. The invention can be implemented with any suitable number of concentric windings.

Advantages of the Invention:

The parallel arrangement of the windings 32, 34, 36 of the coil antenna 30 of FIG. 3A reduces the potential across each winding, as compared to, for example, using only one winding, and therefore reduces the capacitive coupling (as explained above with reference to the example of FIG. 2). In addition, the coil antenna of FIG. 3A provides uniform plasma density over the wafer, as compared previous techniques for example, as there are no discontinuities of the type discussed above with reference to the example of FIG. 2 (e.g., in the RF field). Such improved uniformity is not limited to etch applications, but is also realized when the invention is used in other plasma-assisted processes, such as chemical and physical vapor deposition of coatings. Further, as compared to prior art FIG. 1, not only is the potential across each winding reduced, but also the current flowing in the parallel windings of the invention is spatially distributed over the reaction volume in a much more uniform fashion.

Preferably, each of the windings 32, 34, 36 have the same length and their outer ends 32b, 34b, 36b terminate at points equidistant from each other about a circularly symmetric reaction chamber, further enhancing uniformity. Preferably, the winding inner ends 32a, 34a, 36a terminate at the geometric center of the coil antenna because the apex is located at the geometric center of the coil, which preferably has geometric circular symmetry. Preferably also, this geometric antenna center is made to coincide with the axis of symmetry of a circularly symmetric reactor chamber. Also, the winding inner ends 32, 34a, 36a are preferably spaced equidistantly away from each other for a limited radial distance as they approach the apex terminal 38a. Further, the windings are spaced from each other as uniformly as possible at least in flat configurations of the invention such as the embodiment of FIG. 3A; while in non-flat configurations such as the embodiment of FIG. 8, smoother variations and spacings with radius from the geometrical center may be made to compensate for chamber geometry.

As a result, the RF power applied to the coil antenna of FIG. 3A need not be limited as in the case of the coil antenna of FIG. 1. Indeed, the coil antenna of FIG. 3A can operate with 3000 Watts of RF power at 13.56 MHz, while the coil antenna of FIG. 1 must be limited to about 300 watts to prevent failures due to the nonuniform field coverage. The increase in RF power afforded by the coil antenna of FIG. 3A provides higher etch rates in a plasma etch reactor, higher deposition rates in a chemical vapor deposition reactor. Thus, the invention not only provides greater processing uniformity across the wafer surface but also provides greater throughput or productivity.

The invention provides a greater uniformity of ion density across the wafer surface, a significant advantage. This is illustrated in the superimposed graphs of FIG. 18. The curves in FIG. 18 labelled AI, A2, A3 and A4 represent measurements of ion current at the wafer surface in milliAmperes per square centimeter as a function of distance from the wafer center in centimeters for a reactor employing the coil antenna of the invention depicted in FIG. 3A with a reactor chamber supplied with chlorine gas at an applied RF power level of 2000 Watts on the antenna coil, no RF bias power applied and the chamber maintained at a pressure of 2 milliTorr, 6.2 milliTorr, 10 milliTorr and 4 milliTorr, respectively. The smallest deviation in ion density, namely 2% in the curve labelled AI, is obtained at 2 milliTorr. The uniformity percentage represents the change in current density (vertical axis) across the wafer divided by two times the average current density in that range. In contrast, a reactor sold by manufacturer #1, whose performance is depicted by the curve labelled B in FIG. 18, had a deviation in plasma ion density of 4.5% across the wafer surface at the same applied RF power level and no RF bias power applied and a mixture of 50 parts of chlorine and 20 parts helium. A reactor sold by manufacturer #2, whose performance is depicted by the curve labelled C in FIG. 18, had a deviation in plasma ion density of 9% under similar conditions. A reactor sold by manufacturer #3, whose performance is depicted by the curve labelled D in FIG. 18 had a deviation of 11% in plasma ion density across the wafer surface. A reactor sold by manufacturer #4, whose performance is depicted by the curve labelled E in FIG. 18, had a deviation in plasma ion density across the wafer surface of 26% at an applied power level of 900 Watts on the antenna coil. The foregoing data is summarized in the following table:

TABLE I

Plasma Reactor	Ion Current (mA/cm^2)	Applied Power (Watts)	Pressure (mTorr)	Gas	Ion Density Deviation
Invention	12.8	2000	2	Cl	2%
Manufacturer #1	17	2000	1.2	50Cl/20He	4.5%
Manufacturer #2	11.4	2000	2	Cl	9%
Manufacturer #3	7.6	1450	2	Cl	11%
Manufacturer #4	11.5	900	5	Cl	26%

The invention provides a greater stability of ion density over a large range of chamber pressures, a significant advantage. The performance of two plasma reactors of the prior art sold by manufacturers #2 and #3 are depicted by the superimposed curves labelled C and D, respectively, in FIG. 19. The vertical axis is a normalized measured ion current at the wafer surface while the horizontal axis is the chamber pressure in milliTorr. The manufacturer #2 plasma reactor (curve C) has a deviation of 23% in ion current over a pressure range from 2 to 5 milliTorr. The manufacturer #3 reactor (curve D) has a deviation of 40% in ion current over the same pressure range. The performance of the invention in accordance with FIG. 3A and of other prior art reactors is depicted in the superimposed graphs of FIG. 20. The curves labelled A1, A2, A3 and A4 depict the ion current measured at the wafer surface in the reactor of the invention at distances of 0 cm, 2.9 cm, 5.9 cm and 8.8 cm, respectively, from the wafer center. These curves show that the deviation in ion density using a reactor of the invention is no more than 10% across the same pressure range. The reactor sold by manufacturer #1, whose performance is depicted by the curve labelled B in FIG. 20, had a deviation of 22% across a much narrower pressure range. A reactor sold by manufacturer #5, whose performance is depicted by the curve labelled F in FIG. 20, had a deviation in ion density of 45 across a similar pressure range (2-5 milliTorr). The reactor sold by manufacturer #4, whose performance is depicted by the curve labelled E in FIG. 21, had a deviation in ion density of 25% across the narrower pressure range of .5 to 2.0 milliTorr. The foregoing experimental measurements relating to stability of ion density over change in chamber pressure are summarized in the following table:

TABLE II

Plasma Reactor	Ion Current (mA/cm^2)	Applied Power (Watts)	Pressure (mTorr)	Gas	Ion Density Deviation
Invention	10	2000	2-10	Cl	10%
Manufacturer #1	17	2000	.7-2	50Cl/20He	22%
Manufacturer #2	11.4	2500	2-5	Cl	23%
Manufacturer #3	7.6	1000	2-5	Cl	40%
Manufacturer #4	11.5	300 W (source) 30 W (bias)	2-10	Cl	25%
Manufacturer #5	15	1000	2-5	N	45%

The foregoing experimental data show that the invention provides a stability in ion density over changes in pressure over twice that of the best reactors of the prior art and at least four times that of other reactors of the prior art.

While the invention has been described in detail by specific reference to preferred embodiments, it is understood that variations and modifications may be made without departing from the true spirit and scope of the invention.

Claims

1. A plasma reactor for processing a semiconductor wafer, comprising:

    a vacuum chamber;
    means for introducing a processing gas into said vacuum chamber;
    a wafer pedestal for supporting said semiconductor wafer inside said vacuum chamber;
    an RF power source;
    a coil antenna near said vacuum chamber, said coil antenna comprising:

plural concentric spiral conductive windings, each of said windings having an interior end near an apex of a spiral of the winding and an outer end at a periphery of the spiral of the winding, and
a common terminal connected to the interior ends of said plural concentric spiral windings, said RF power source being connected across said terminal and the outer end of each one of said windings.

2. The plasma reactor of Claim 1 wherein said RF power source comprises two terminals, one of said two terminals being an RF power terminal and the other of said two terminals being an RF return terminal which is connected to ground, said common terminal of said plural concentric spiral conductive windings being connected to ground and said outer ends of said plural concentric spiral conductive windings being connected to said RF power terminal.

3. The plasma reactor of Claim 1 wherein said reactor chamber comprises a planar ceiling and said antenna coil has a planar disk shape and lies on an exterior surface of said ceiling.

4. The plasma reactor of Claim 1 wherein said reactor chamber comprises a cylindrical side wall and said antenna coil has a cylindrical shape and is lies on a portion of said cylindrical wall.

5. The plasma reactor of Claim 1 wherein said reactor comprises a dome-shaped ceiling and said antenna coil has a dome shape and lies on and is congruent with at least a portion of said dome-shaped ceiling.

6. The plasma reactor of Claim 1 wherein said reactor comprises a truncated dome-shaped ceiling and said antenna coil has a truncated dome shape and lies on and is congruent with at least a portion of said truncated dome-shaped ceiling.

7. The plasma reactor of Claim 1 wherein said reactor chamber comprises a planar ceiling and a cylindrical side wall and one portion of said antenna coil is planar and overlies said planar ceiling while another portion of said antenna coil is cylindrical and lies on at least a portion of said cylindrical side wall.

8. The plasma reactor of Claim 1 wherein said reactor comprises a dome-shaped ceiling and a cylindrical side wall and one portion of said antenna coil is dome-shaped and overlies and is congruent with said dome-shaped ceiling and another portion of said coil antenna is cylindrical and lies on at least a portion of said cylindrical side wall.

9. The plasma reactor of Claim 1 wherein said reactor comprises a truncated dome-shaped ceiling and a cylindrical side wall and one portion of said antenna coil has a truncated dome-shape and overlies and is congruent with said truncated dome-shaped ceiling and another portion of said coil antenna is cylindrical and lies on at least a portion of said cylindrical side wall.

10. The plasma reactor of Claim 1 wherein said plural windings are of about the same length.

11. The plasma reactor of Claim 1 wherein said coil antenna comprises three of said windings.

12. The plasma reactor of Claim 11 wherein said inner ends are circumferentially spaced from one another at equal intervals and wherein said outer ends are circumferentially spaced from one another at equal intervals.

13. The plasma reactor of Claim 1 further comprising a bias RF source connected to said wafer pedestal.

14. The plasma reactor of Claim 1 wherein said chamber comprises a sidewall and a ceiling overlying said sidewall, a first portion of said coil antenna conformally overlying said sidewall and a second portion of said antenna conformally overlying said ceiling, there being a smooth transition between said first and second portions of said antenna.

15. The plasma reactor of Claim 12 wherein said inner ends of said windings are radially spaced from said apex and connected to said common terminal by respective straight line symmetrically spaced conductors.

16. The plasma reactor of Claim 15 wherein said common terminal is displaced vertically above a plane of said inner ends of said windings and said straight line conductors wick upwardly away from said inner ends toward said common terminal.

17. The plasma reactor of Claim 14 wherein said ceiling comprises a central portion having a characteristic shape and

an outer annular chamber having a curvature providing a smooth transition between said sidewall and said central portion of said ceiling, and wherein said second portion of said antenna comprises a first subportion conformally overlying said central portion of said ceiling and a second subportion conformally overlying said chamber, said second subportion smoothly transitioning between said ceiling and said sidewall.

18. The plasma reactor of Claim 17 wherein said characteristic shape is a hemispherical dome.

19. The plasma reactor of Claim 17 wherein said characteristic shape is a disc.

20. The plasma reactor of Claim 17 wherein said characteristic shape is a portion of a hemispherical dome.

21. A coil antenna for radiating RF power supplied by an RF source into a vacuum chamber of an inductively coupled plasma reactor which processes a semiconductor wafer in said vacuum chamber, said reactor having a gas supply inlet for supplying processing gases into said vacuum chamber, said coil antenna comprising:

plural concentric spiral conductive windings, each of said windings having an interior end near an apex of a spiral of the winding and an outer end at a periphery of the spiral of the winding, and
a common terminal connected to the interior ends of said plural concentric spiral windings, said RF power source being connected across said terminal and the outer end of each one of said windings.

22. The plasma reactor of Claim 21 wherein said RF power source comprises two terminals, one of said two terminals being an RF power terminal and the other of said two terminals being an RF return terminal which is connected to ground, said common terminal of said plural concentric spiral conductive windings being connected to ground and said outer ends of said plural concentric spiral conductive windings being connected to said RF power terminal.

23. The plasma reactor of Claim 21 wherein said reactor chamber comprises a planar ceiling and said antenna coil has a planar disk shape and lies on an exterior surface of said ceiling.

24. The plasma reactor of Claim 21 wherein said reactor chamber comprises a cylindrical side wall and said antenna coil has a cylindrical shape and is lies on a portion of said cylindrical wall.

25. The plasma reactor of Claim 21 wherein said reactor comprises a dome-shaped ceiling and said antenna coil has a dome shape and lies on and is congruent with at least a portion of said dome-shaped ceiling.

26. The plasma reactor of Claim 21 wherein said reactor comprises a truncated dome-shaped ceiling and said antenna coil has a truncated dome shape and lies on and is congruent with at least a portion of said truncated dome-shaped ceiling.

27. The plasma reactor of Claim 21 wherein said reactor chamber comprises a planar ceiling and a cylindrical side wall and one portion of said antenna coil is planar and overlies said planar ceiling while another portion of said antenna coil is cylindrical and lies on at least a portion of said cylindrical side wall.

28. The plasma reactor of Claim 21 wherein said reactor comprises a dome-shaped ceiling and a cylindrical side wall and one portion of said antenna coil is dome-shaped and overlies and is congruent with said dome-shaped ceiling and another portion of said coil antenna is cylindrical and lies on at least a portion of said cylindrical side wall.

29. The plasma reactor of Claim 21 wherein said reactor comprises a truncated dome-shaped ceiling and a cylindrical side wall and one portion of said antenna coil has a truncated dome-shape and overlies and is congruent with said truncated dome-shaped ceiling and another portion of said coil antenna is cylindrical and lies on at least a portion of said cylindrical side wall.

30. The plasma reactor of Claim 21 wherein said plural windings are of about the same length.

31. The plasma reactor of Claim 21 wherein said coil antenna comprises three of said windings.

32. The plasma reactor of Claim 31 wherein said inner ends are circumferentially spaced from one another at equal intervals and wherein said outer ends are circumferentially spaced from one another at equal intervals.

33. The plasma reactor of Claim 21 further comprising a bias RF source connected to said wafer pedestal.

34. The plasma reactor of Claim 21 wherein said chamber comprises a sidewall and a ceiling overlying said sidewall, a first portion of said coil antenna conformally overlying said sidewall and a second portion of said antenna conformally overlying said ceiling, there being a smooth transition between said first and second portions of said antenna.

35. The plasma reactor of Claim 32 wherein said inner ends of said windings are radially spaced from said apex and connected to said common terminal by respective straight line symmetrically spaced conductors.

36. The plasma reactor of Claim 35 wherein said common terminal is displaced vertically above a plane of said inner ends of said windings and said straight line conductors wick upwardly away from said inner ends toward said common terminal.

37. The plasma reactor of Claim 34 wherein said ceiling comprises a central portion having a characteristic shape and an outer annular chamber having a curvature providing a smooth transition between said sidewall and said central portion of said ceiling, and wherein said second portion of said antenna comprises a first subportion conformally overlying said central portion of said ceiling and a second subportion conformally overlying said chamber, said second subportion smoothly transitioning between said ceiling and said sidewall.

38. The plasma reactor of Claim 37 wherein said characteristic shape is a hemispherical dome.

39. The plasma reactor of Claim 37 wherein said characteristic shape is a disc.

40. The plasma reactor of Claim 37 wherein said characteristic shape is a portion of a hemispherical dome.

41. The plasma reactor of Claim 21 wherein said vacuum chamber is circularly symmetrical and said concentric windings of said coil antenna are circularly symmetrical having a common axis of symmetry with said vacuum chamber.

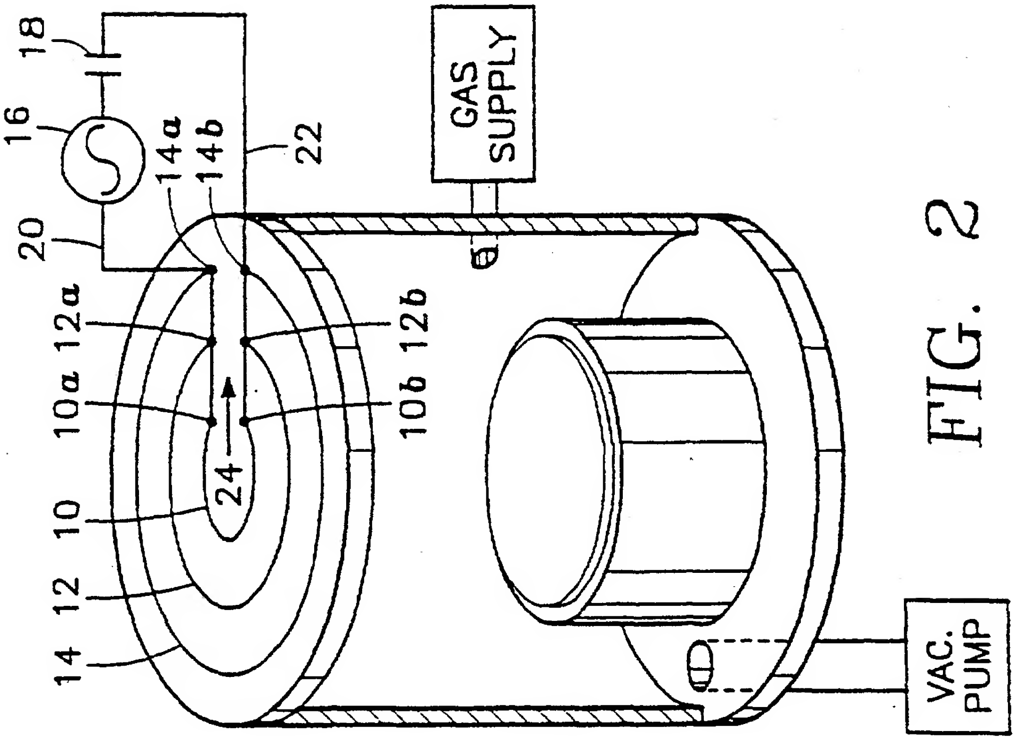
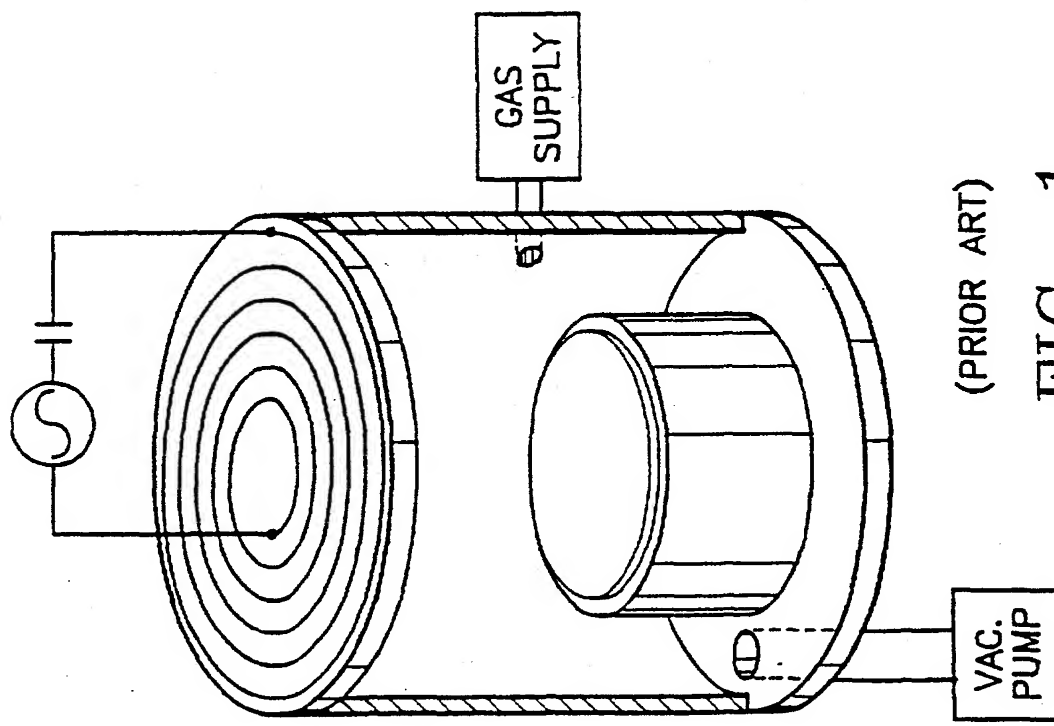


FIG. 2



(PRIOR ART)
FIG. 1

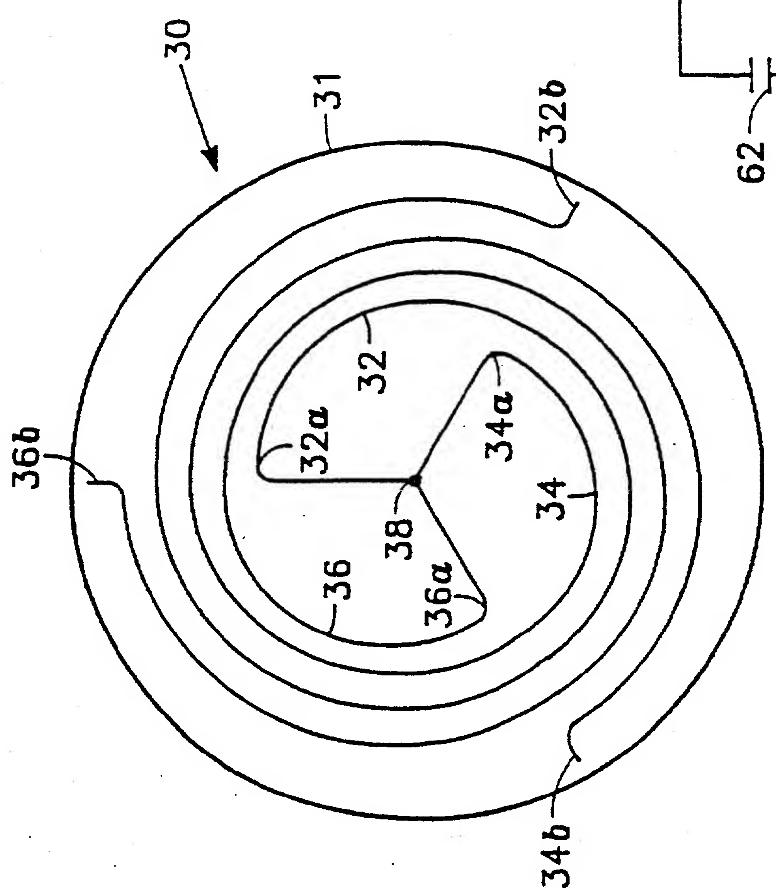

30
31
32b
32
32a
34a
34
38
36
36a
36b
34b

FIG. 3A

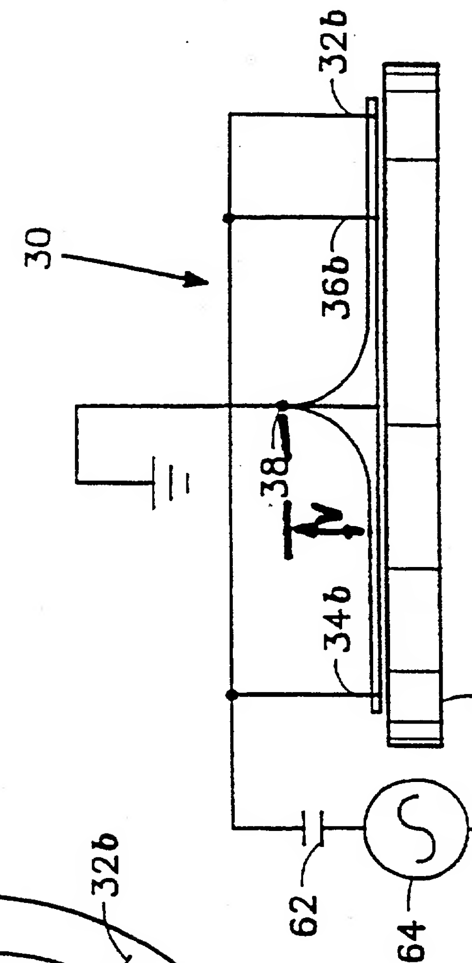

30
32b
36b
38
V
34b
31
62
64

FIG. 4

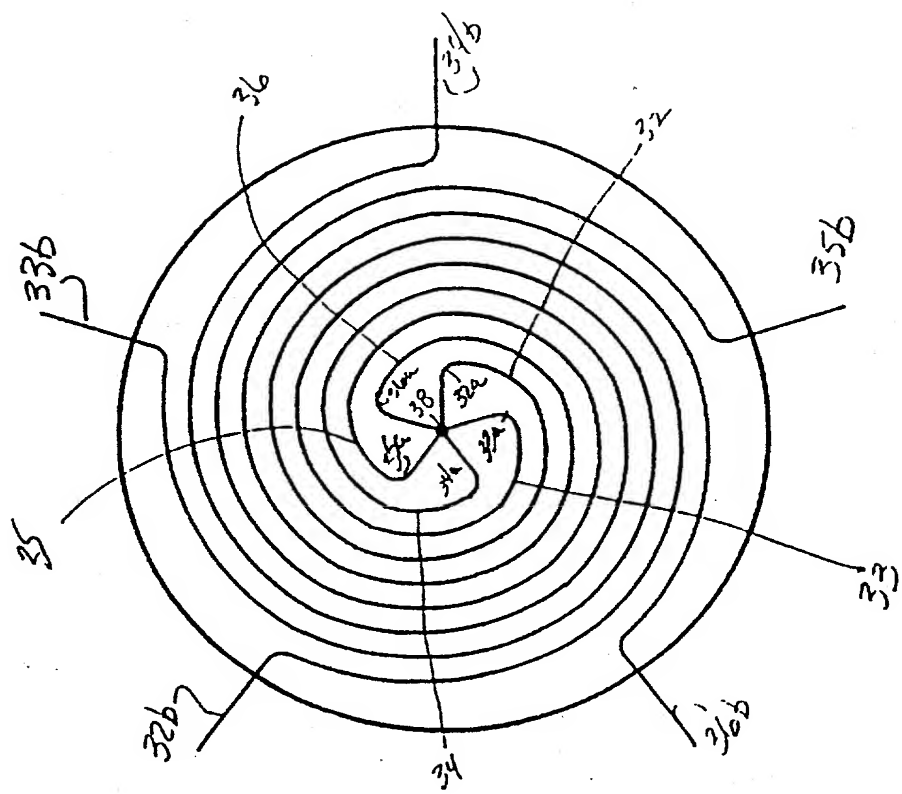


FIG. 3B

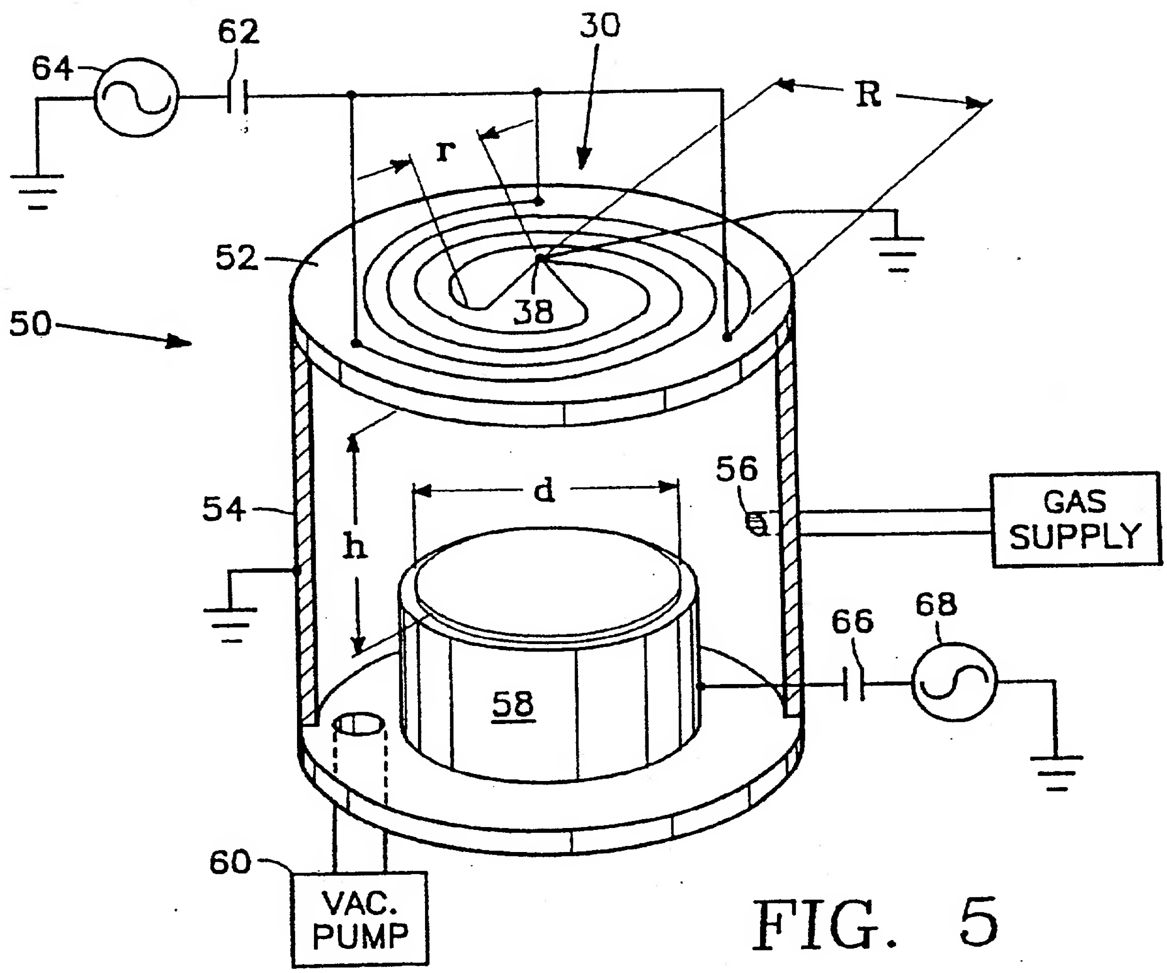


FIG. 5

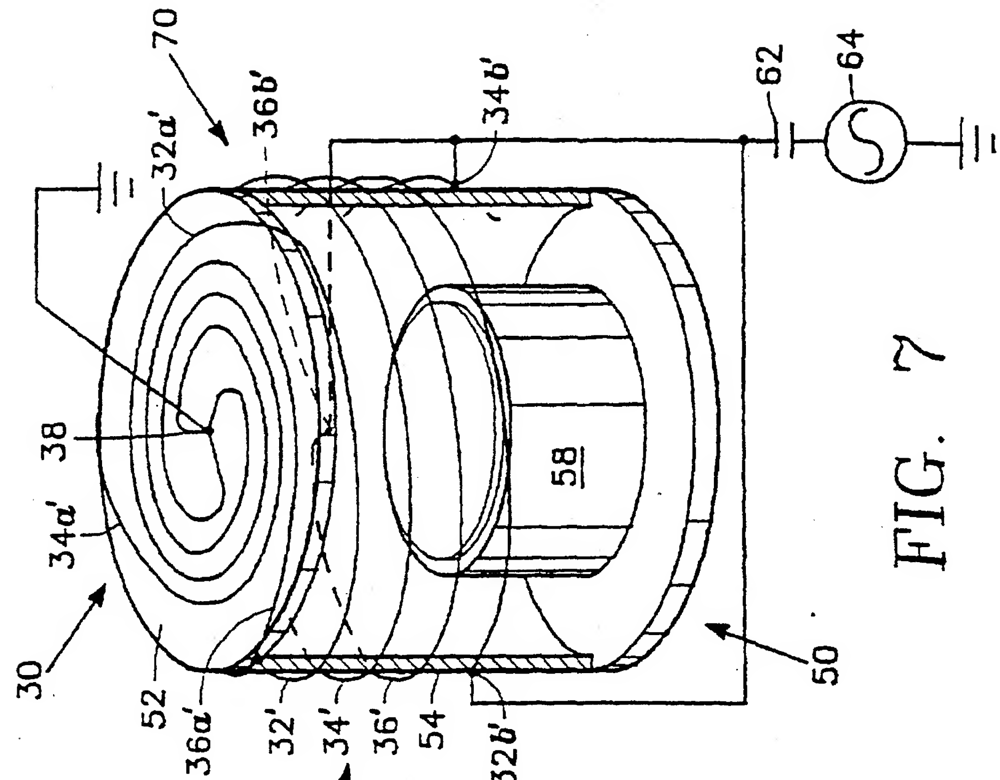

30
34a'
38
32a'
70
36b'
34b'
62
64
52
36a'
32'
34'
36'
54
32b'
58
50

FIG. 7

40

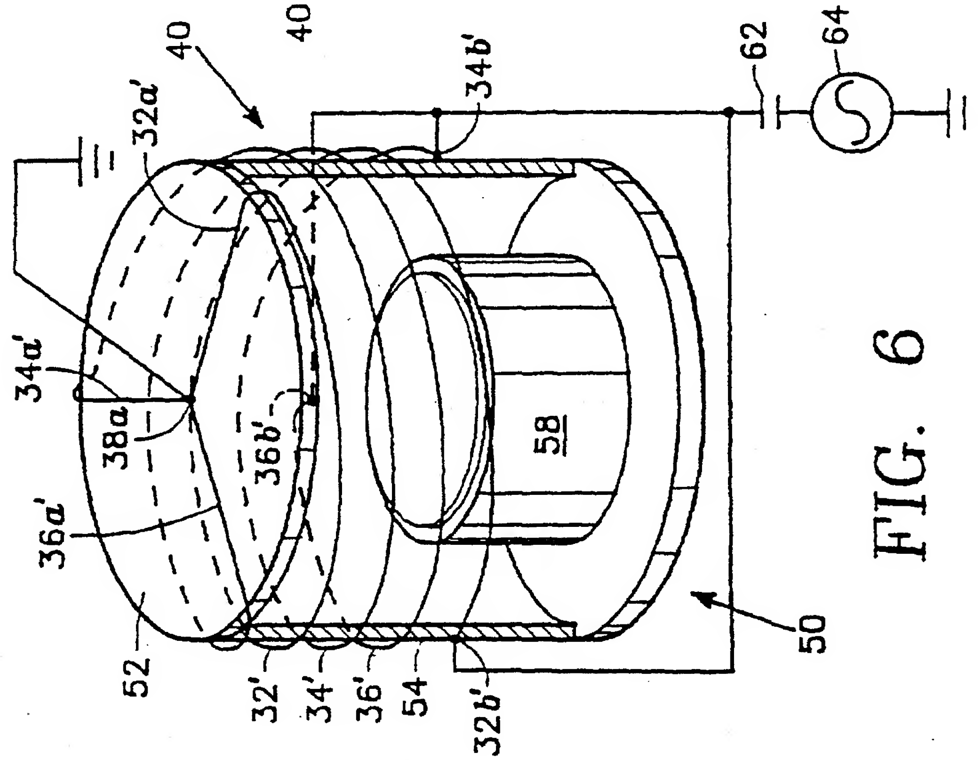

40
32a'
34a'
38a
36b'
36a'
34b'
62
64
52
32'
34'
36'
54
32b'
58
50

FIG. 6

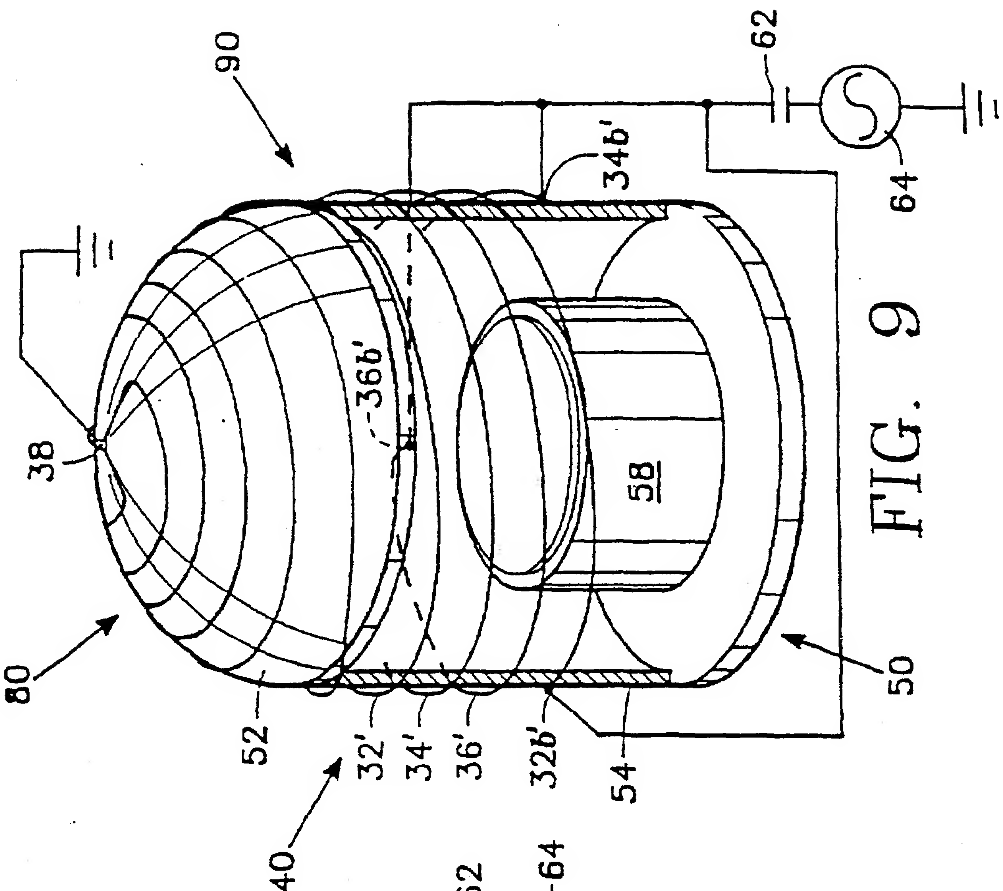

90
38
80
36b'
34b'
62
64
58
52
32'
34'
36'
32b'
54
50
40

FIG. 9

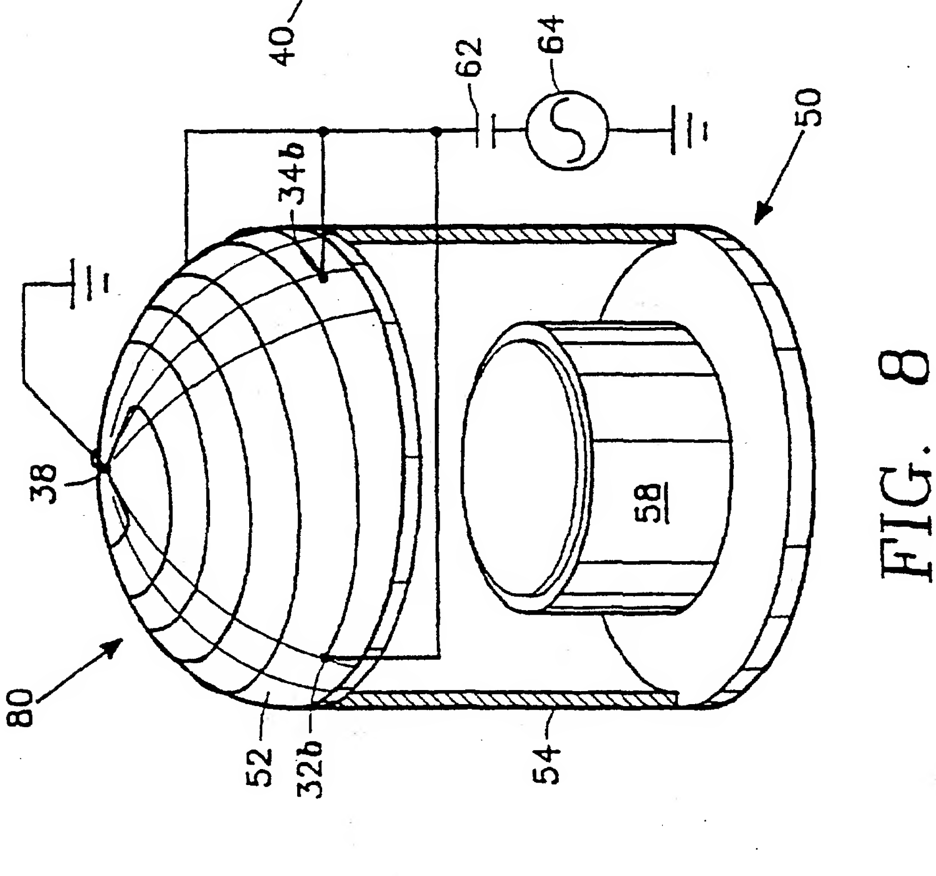

38
80
34b
62
64
50
58
52
32b
54

FIG. 8

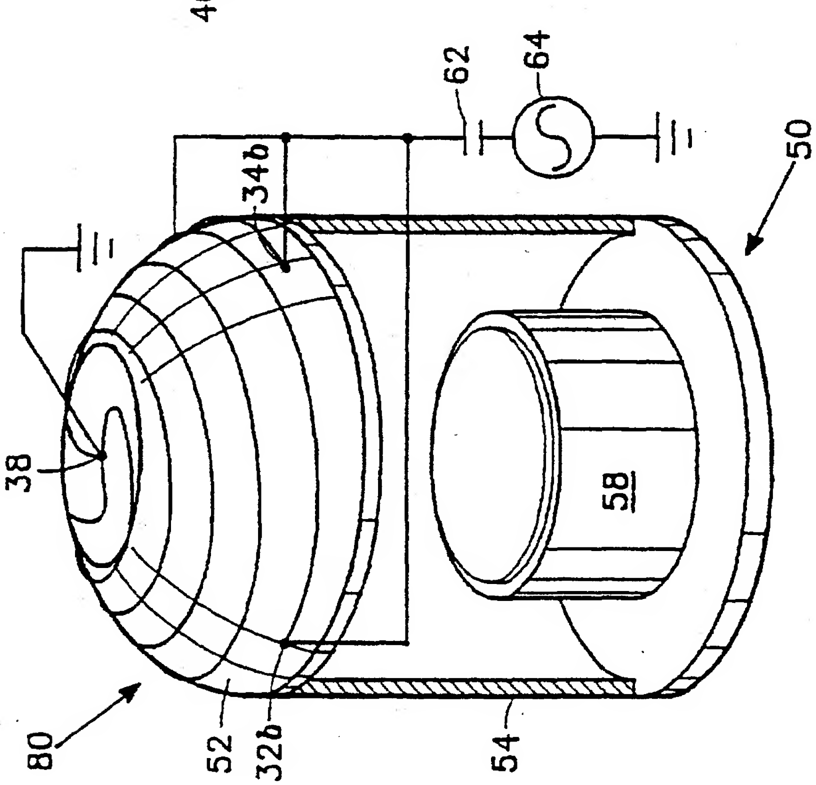

80
52
32b
54
38
34b
62
64
58
50

FIG. 10

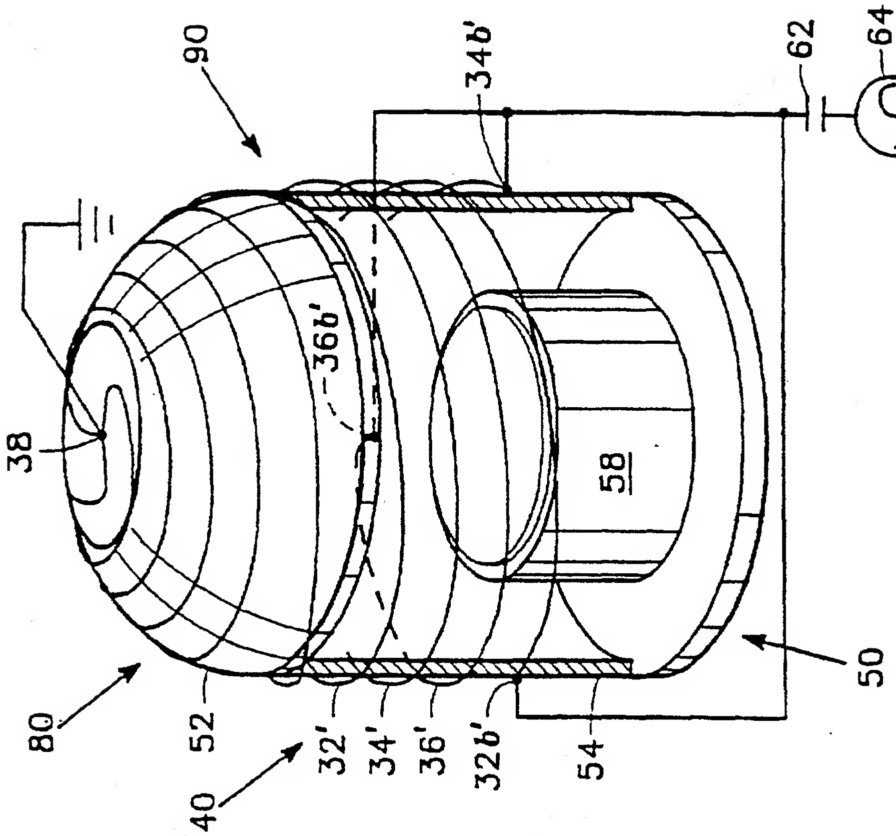

80
52
40
32'
34'
36'
32b'
54
38
36b'
90
34b'
62
64
58
50

FIG. 11

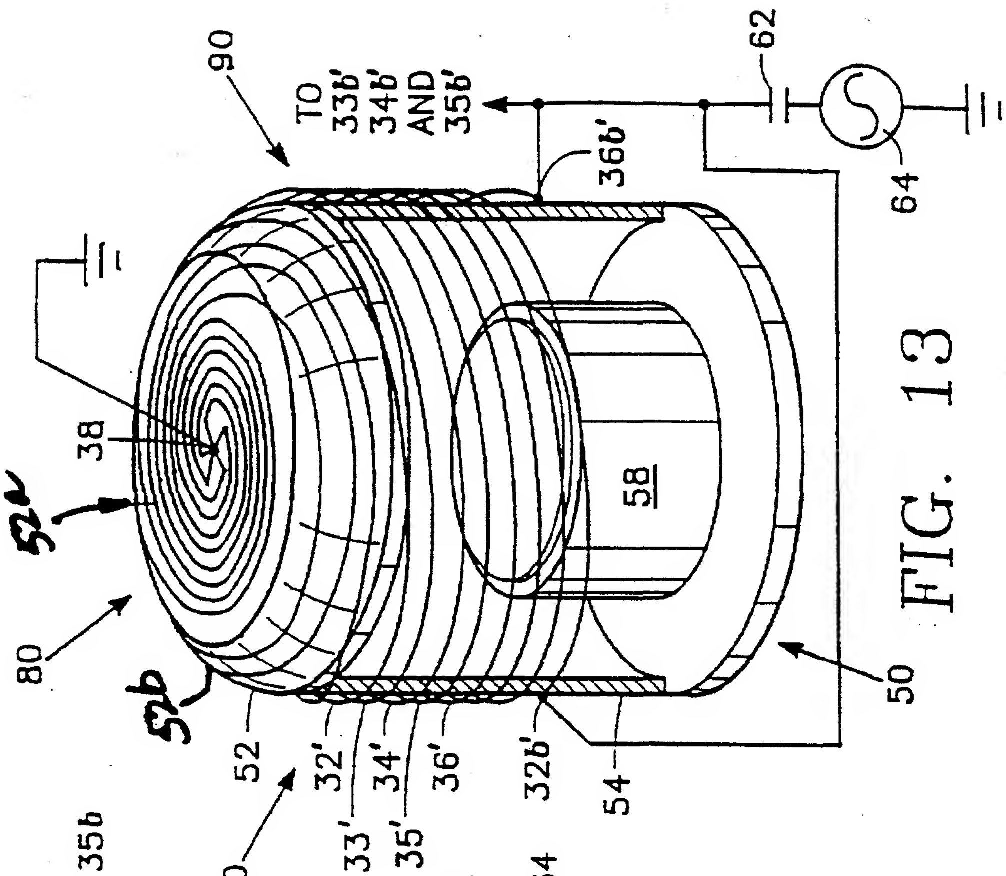

90
TO
33b'
34b'
AND
35b'
62
36b'
64
38
52a
80
52b
52
32'
33'
34'
35'
36'
32b'
54
58
50
40

FIG. 13

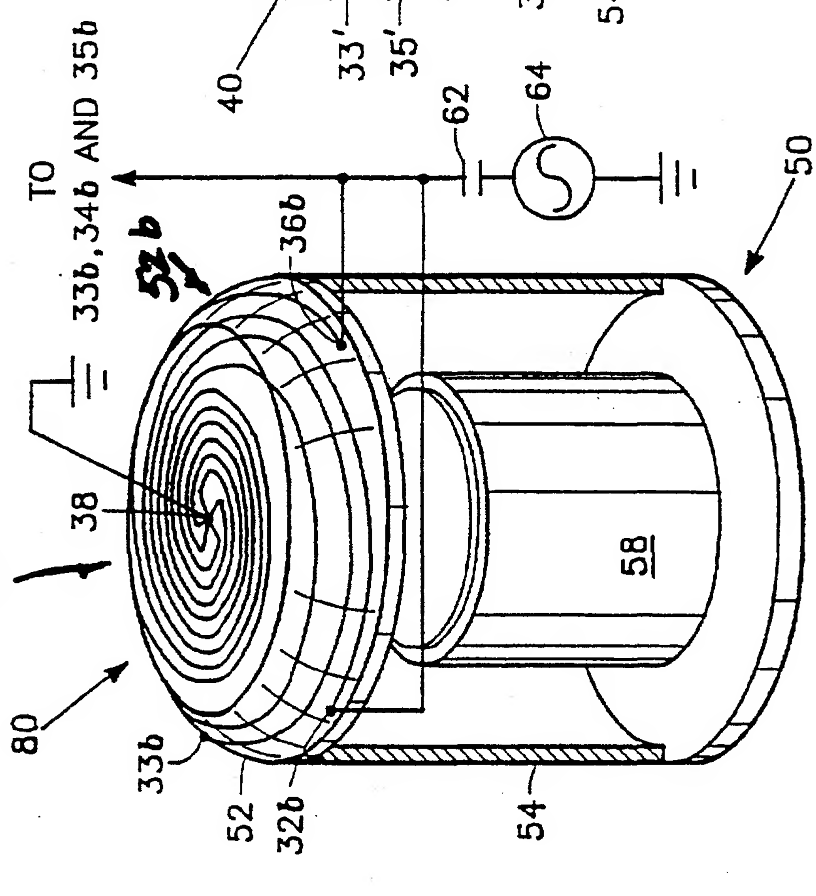

TO
33b, 34b AND 35b
52b
36b
62
64
52a
38
80
33b
52
32b
54
58
50

FIG. 12

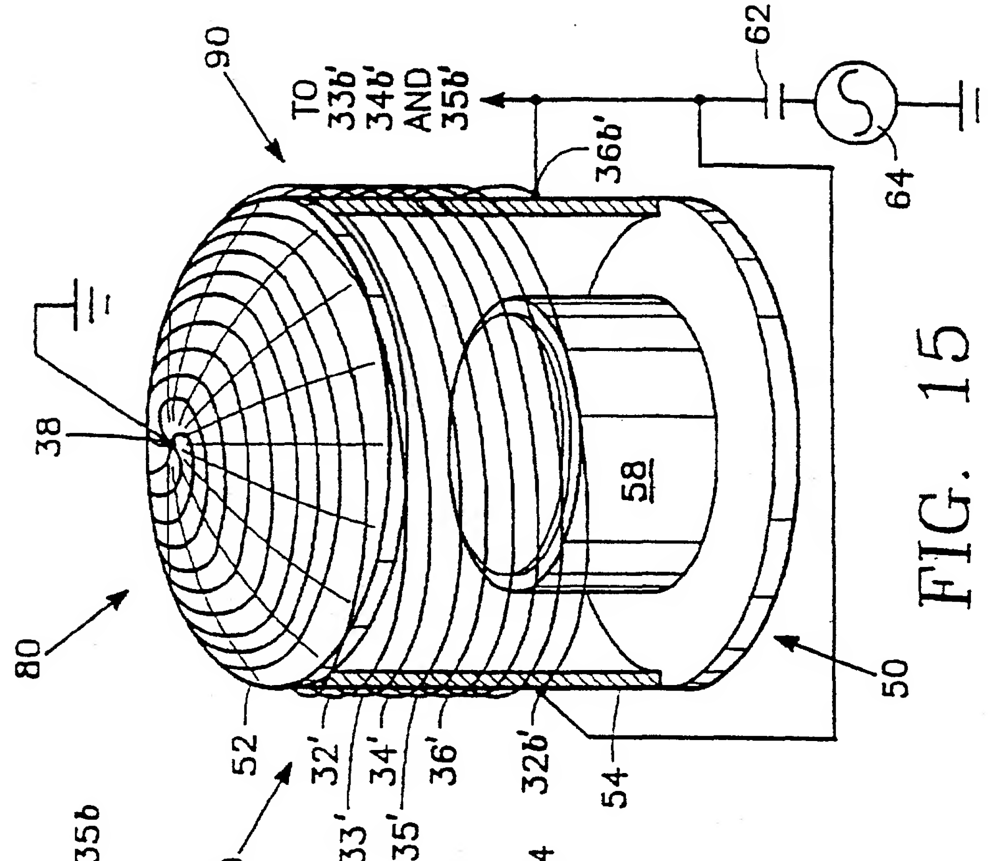

90
TO
33b'
34b'
AND
35b'
62
36b'
64
38
80
58
52
32'
34'
36'
32b'
54
50
40
33'
35'

FIG. 15

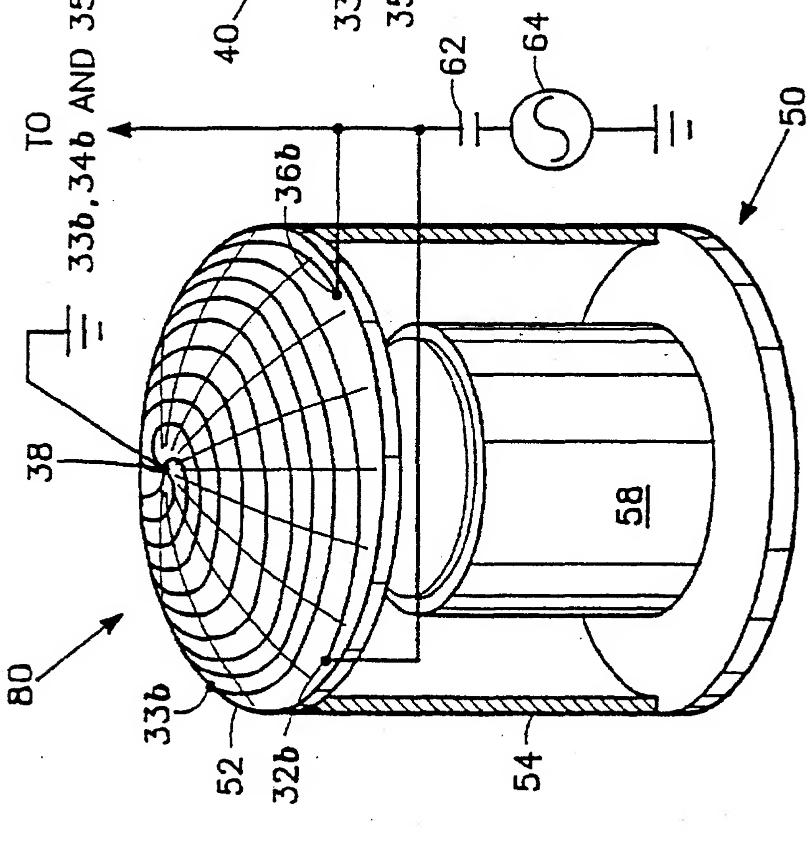
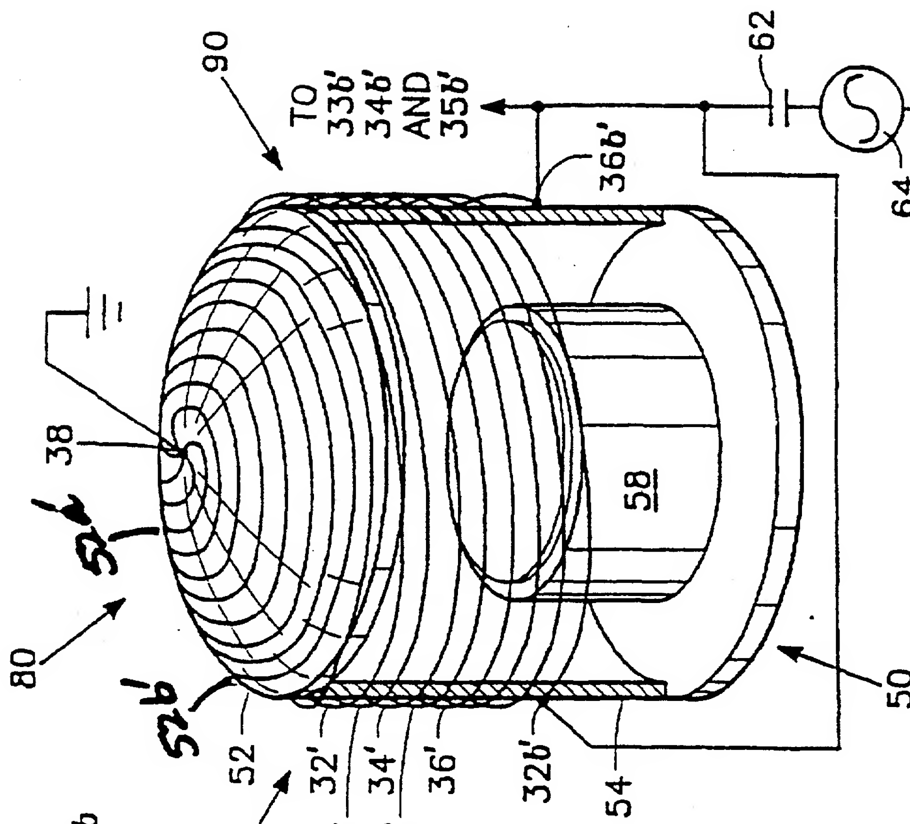
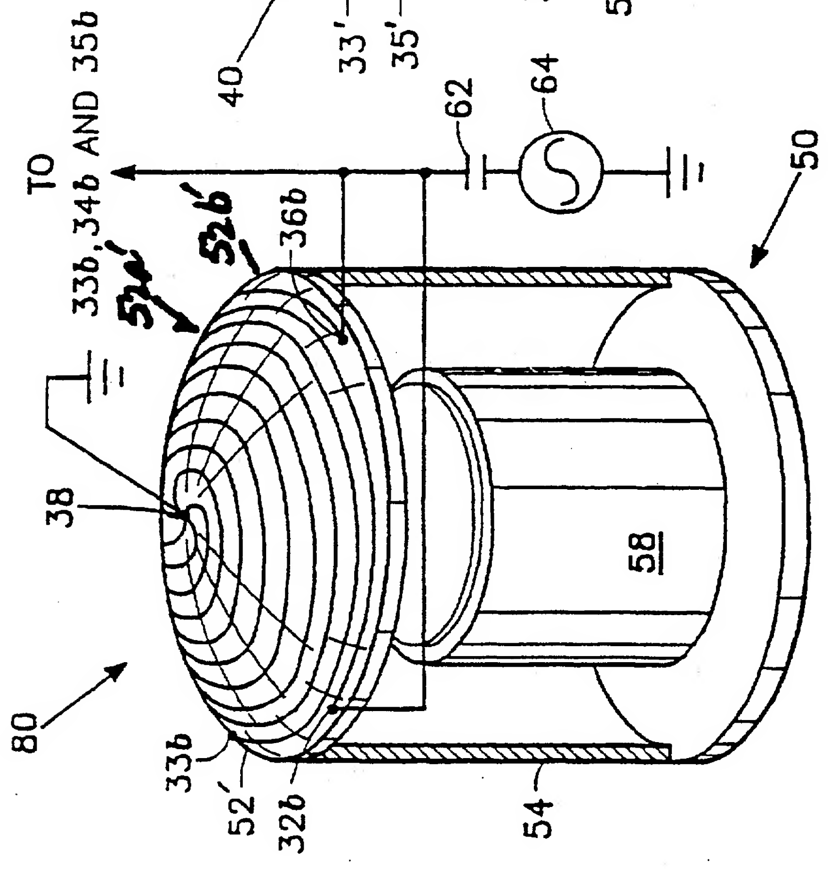

TO
33b, 34b AND 35b
62
64
36b
38
80
33b
52
32b
58
54
50

FIG. 14



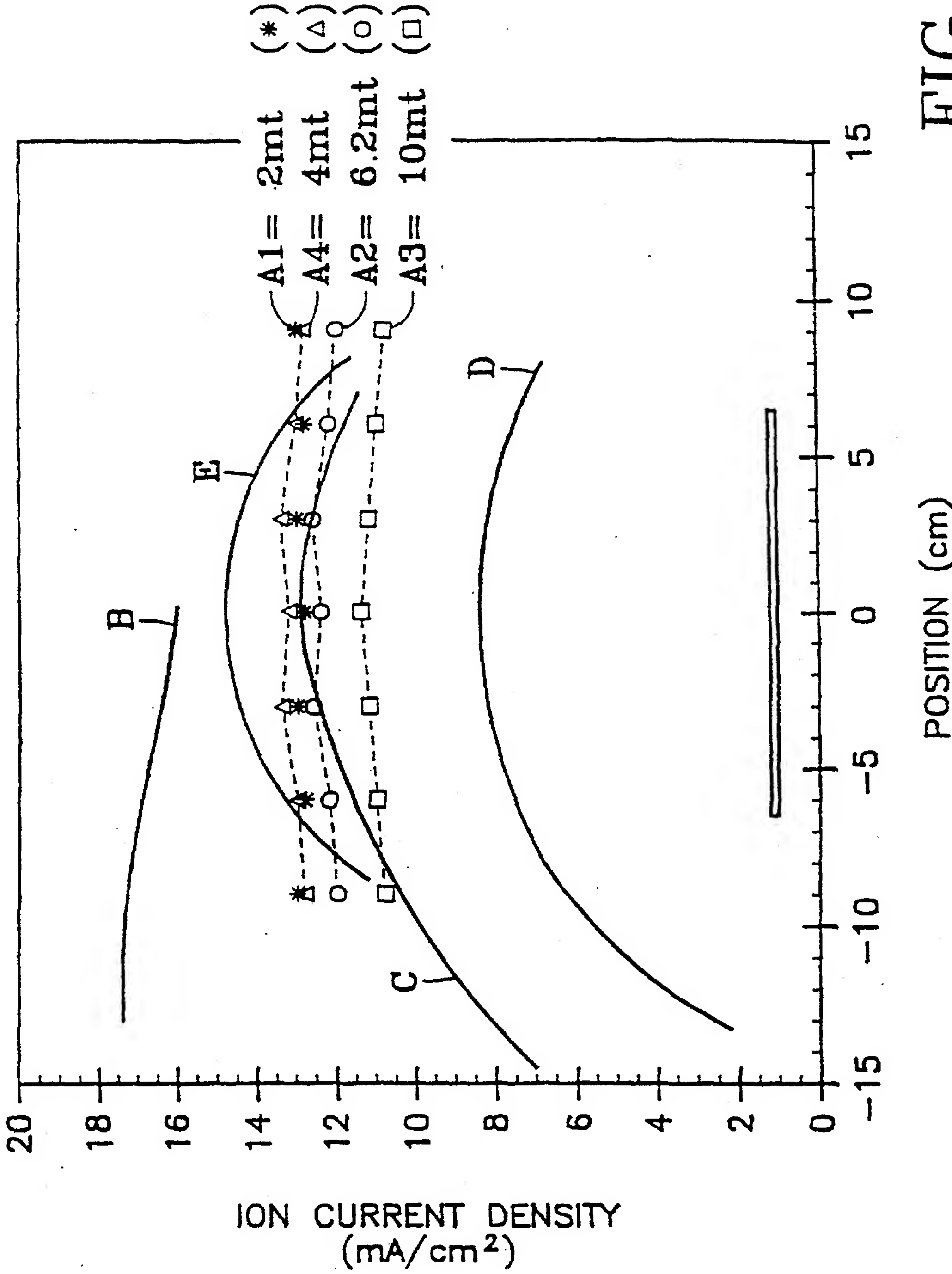
90
TO 33b' 34b' AND 35b'
62
64
36b'
38
52b'
80
52b'
52
40
32'
33'
34'
35'
36'
32b'
54
58
50

FIG. 17



80
38
33b
52'
32b
54
58
TO 33b, 34b AND 35b
52a'
52b'
36b
62
64
50

FIG. 16



A1= 2mt (*)
A4= 4mt (△)
A2= 6.2mt (○)
A3= 10mt (□)
B
C
D
E
ION CURRENT DENSITY (mA/cm²)
20
18
16
14
12
10
8
6
4
2
0
POSITION (cm)
−15
−10
−5
0
5
10
15

FIG. 18

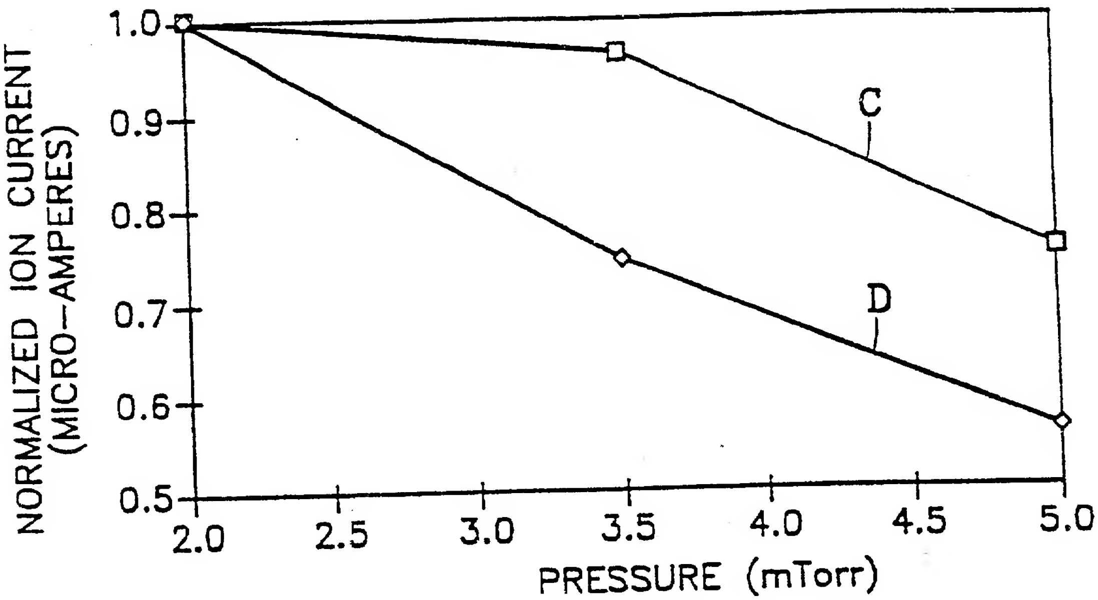

NORMALIZED ION CURRENT
(MICRO-AMPERES)
1.0
0.9
0.8
0.7
0.6
0.5
C
D
2.0
2.5
3.0
3.5
4.0
4.5
5.0
PRESSURE (mTorr)

FIG. 19

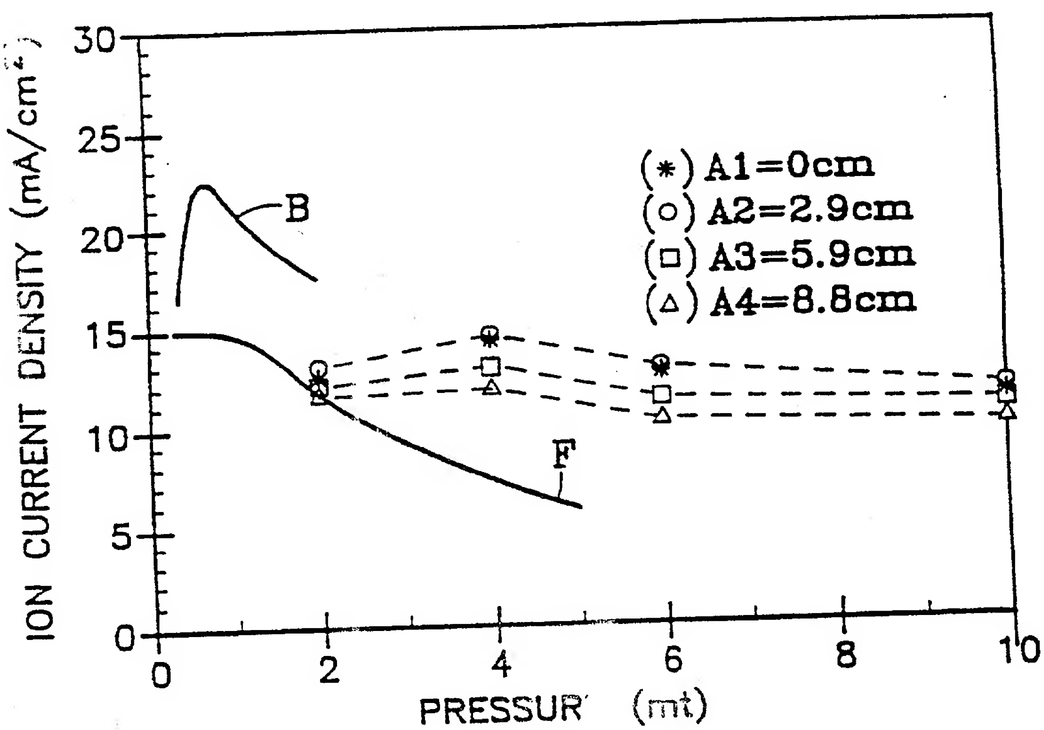

ION CURRENT DENSITY (mA/cm²)
30
25
20
15
10
5
0
B
F
(*) A1=0cm
(○) A2=2.9cm
(□) A3=5.9cm
(△) A4=8.8cm
0
2
4
6
8
10
PRESSUR (mt)

FIG. 20

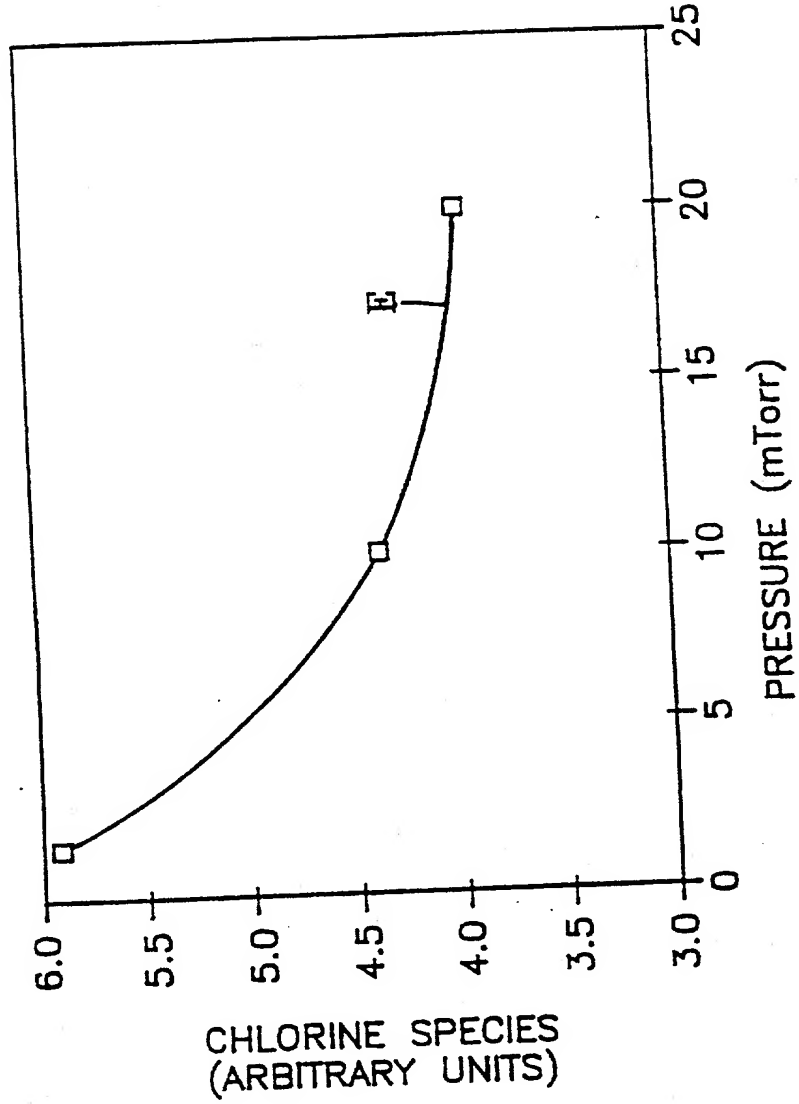

CHLORINE SPECIES
(ARBITRARY UNITS)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
0
5
10
15
20
25
PRESSURE (mTorr)
E

FIG. 21

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 95 30 7268

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	EP-A-0 596 551 (NOVELLUS SYSTEMS INC) 11 May 1994 * column 2, line 53 - column 3, line 25 * * column 6, line 17 - line 26 * * figure 5 *	1,5,8, 12-14, 25,28, 32-34,41	H05H1/46 H01J37/32
A	WO-A-91 10341 (SAVAS STEPHEN E) 11 July 1991 * page 12, line 24 - line 30 * * figure 4 *	4,17,19, 24,37,39	
A	GB-A-2 231 197 (NORDIKO LTD ;ATOMIC ENERGY AUTHORITY UK (GB)) 7 November 1990 * figures 1,2 *	1,5,13, 25,33,41	
A	US-A-5 194 731 (TURNER IAN L) 16 March 1993 * column 3, line 21 - line 60 * * column 4, line 52 - line 56 * * figures 1,2 *	1,2,10, 21,22,30	TECHNICAL FIELDS SEARCHED (Int.Cl.6) H05H H01J
D,A	EP-A-0 413 282 (LAM RES CORP) 20 February 1991		

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	2 February 1996	Capostagno, E

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
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P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
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